1   Economics of size-structured forestry with carbon storage

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Abstract

We study the economics of carbon storage using a model that includes forest size structure and determines the choice between rotation forestry and continuous cover forestry. Optimal harvests may rely solely on thinning, implying infinite rotation and continuous cover forestry, or both thinning and clearcuts, implying finite rotation periods. Given several carbon prices and interest rates, we optimize the timing and intensity of thinnings along with the choice of management regime. In addition to the carbon storage in living trees, we include the carbon dynamics of dead trees and timber products. Forest growth is specified by an empirically validated transition matrix model for Norway spruce (*Picea abies* (L.) Karst.). The optimization problem is solved in its general dynamic form by applying bilevel optimization with gradient-based interior point methods and a genetic algorithm. Carbon pricing postpones thinnings, increases stand density by directing harvests to larger trees, and typically yields a regime shift from rotation forestry to continuous cover forestry. In continuous cover solutions, the steady-state harvesting interval and the diameter distribution of standing and harvested trees are sensitive to carbon price, implying that carbon pricing increases the sawlog ratio of timber yields. Additionally, we obtain relatively inexpensive stand-level marginal costs of carbon storage.

1. Introduction

Holding more than double the amount of carbon in the atmosphere, forest ecosystems are a crucial part of the global carbon cycle (FAO 2006). Carbon storage in forests can be maintained and increased by reducing deforestation, by afforestation and by changing stand-level forest management practices (IPCC 2014). While increasing forest cover may be challenging due to competing land uses (Lubowski et al. 2006), enhancing carbon storage per hectare of existing forestland may be a cost-efficient mitigation option. Our study analyses economically optimal carbon storage in size-structured stands of Norway spruce (*Picea abies* (L.) Karst.). Unlike previous studies, we apply a forest economic model that encompasses the two alternative forest management regimes: forest management based on clearcuts and management that maintains forest cover continuously. Using this generalized model, we present a detailed analysis of the effects of carbon storage on optimal management practices, including the choice between management regimes. The latter is vital given that climate change adaptation and biodiversity protection may motivate a more widespread application of continuous cover management (Gauthier et al. 2015).

In the boreal region and beyond, forestry has relied heavily on the rotation regime, where forest stands are artificially regenerated and finally clearcut, resulting in more or less even-aged stands (Gauthier et al. 2009). However, planted even-aged forests account for only 13% of managed forest area globally (FAO 2010, Payn et al. 2015). Further, recent research suggests that plantation forestry may be more vulnerable to disturbances related to climate change than forest management that maintains structurally diverse stands (Gauthier et al. 2015). An alternative to the rotation regime is continuous cover or uneven-aged forestry, where the stand is managed by partial cuttings (i.e. thinnings). Regeneration occurs naturally, resulting in a heterogeneous age and size distribution. In comparison to rotation forestry, continuous cover forestry is likely to support more biodiversity and other ecosystem services (Calladine et al. 2015, O'Hara 2014) and to be more resilient against threats brought about by climate change (Thompson et al. 2009).

64   While continuous cover forestry shows promise for climate change adaptation, cost-efficient

65   mitigation measures have been analysed almost exclusively in the framework of rotation forestry. A

66   seminal paper by van Kooten et al. (1995) examines the effect of carbon pricing on optimal rotation

67   age and supply of carbon services. Akao (2011) shows how the effects of carbon storage on optimal

68   rotation age depend on assumptions concerning the carbon release from wood products, while Hoel

69   et al. (2014) extend the van Kooten et al. (1995) framework by including forests' multiple carbon

70   pools, harvest residues and the use of timber for bioenergy. These along with numerous other studies

71   apply the generic version of the Faustmann optimal rotation model, where stands can be harvested

72   solely by clearcutting (Samuelson 1976). As commercial thinnings have an important role in e.g.

73   Nordic context, they have been incorporated into even-aged models with carbon storage by e.g.

74   Huang and Kronrad (2006), Pohjola and Valsta (2007) and Daigneault et al. (2010). Further,

75   Niinimäki et al. (2013) for Norway spruce and Pihlainen et al. (2014) for Scots pine highlight the

76   importance of adapting thinning strategies (in addition to the rotation period) for economically

77   optimal carbon storage.

78   Studies on optimal carbon storage in continuous cover forestry are scarce, and most of the

79   existing contributions have limited their scope to steady states (e.g. Buongiorno et al. 2012). Goetz

80   et al. (2010) is an exception, as they dynamically optimize timber production and carbon storage in

81   uneven-aged stands of Scots pine in Spain. The question of the relative profitability of rotation *vs.*

82   continuous cover forestry in the co-production of timber and carbon storage has been touched upon

83   in certain studies: Gutrich and Howarth (2007) compare management regimes with carbon storage,

84   but do not optimize the regime choice, while Pukkala et al. (2011) analyse the choice of management

85   regime applying a model without sound economic basis. As far as we know, no studies exist using a

86   detailed dynamic model for analysing the effect of carbon storage on the choice between these two

87   management regimes.

This gap is not surprising, as up to very recently, the economics of even- and uneven-aged forestry have been analysed separately and with divergent models. While the literature on even-aged forestry builds on Faustmann (1849), the first attempts to optimize uneven-aged management include de Liocourt (1898) and Adams and Ek (1974). As discussed in Getz and Haight (1989, p. 287–295) and Rämö and Tahvonen (2014), many studies have attempted to bypass the dynamic complexities involved in optimizing uneven-aged forestry. However, seminal contributions by Haight (1985) and Haight and Getz (1987) correctly specify the uneven-aged problem as an infinite time horizon problem without *ad hoc* restrictions. Recently it has been shown that when the optimal choice between continuous cover *vs.* rotation forestry is determined endogenously, both management regimes can be analysed using the same model (Tahvonen and Rämö 2016). This generalized approach allows for the optimization of stand management – thinnings and the (potentially infinite) rotation age – over an infinite time horizon given any initial state. The study at hand extends this model by including the social value of carbon storage.

Our present study is the first one to apply an empirically validated size-structured growth model to the problem of optimal carbon storage with endogenous choice of management regime. Our study features a detailed economic setup with empirically estimated variable harvesting cost functions, along with fixed harvesting costs that necessitate the optimization of thinning intervals. This not only allows us to obtain the first results on optimal harvest timing in uneven-aged forestry with carbon storage, but is also essential for accurately determining the relative economic performance of the rotation and continuous cover regimes. The effect of carbon storage on the optimal choice between these regimes is a question with major practical implications, but one that has not been satisfactorily studied in the previous literature. Our carbon storage formulation explicitly includes carbon dynamics in the whole tree biomass, in dead tree matter and in timber products with distinct decay rates for sawlog and pulpwood products. By combining detailed economic and ecological models, and by

112   optimizing not only rotation age but thinnings and the management regime as well, we are able to

113   determine the most cost-efficient methods for enhancing carbon storage in managed forests.

114   We continue by introducing the growth model and the optimization problem. Thereafter we

115   present the empirical parameter values and the computational methods. This is followed by results on

116   optimal stand management, on timber production and carbon storage, and on forestry revenues and

117   carbon storage costs. Finally, we discuss our results by comparing them with earlier studies and draw

118   conclusions.

119   2. The growth model and the optimization problem

120   We denote the number of trees in size class s at the beginning of period t by

121   x_{st}, $s = 1, 2, ..., n$, $t = t_1, t_1 + 1, ..., T+1$. Accordingly, the stand state at period t can be given as

122    $\mathbf{x}_t = [x_{1t}, x_{2t}, ..., x_{nt}]$. Let us denote the fraction of trees moving to size class $s+1$ at period t by

123    $\beta_s(\mathbf{x}_t)$, $s = 1, 2, ..., n$, where $\beta_n(\mathbf{x}_t) \equiv 0$. The natural mortality in size class s at period t is

124    $\mu_s(\mathbf{x}_t)$, $s = 1, 2, ..., n$. Thus the fraction of trees remaining in the same size class equals

125    $1 - \beta_s(\mathbf{x}_t) - \mu_s(\mathbf{x}_t)$, $s = 1, 2, ..., n$. Natural regeneration is described by ingrowth, i.e. trees entering

126   the smallest size class. Ingrowth at the beginning of period t is denoted by $\phi(\mathbf{x}_t)$. Additionally, we

127   denote the number of trees harvested from size class s at the end of period t by

128   h_{st}, $s = 1, 2, ..., n$, $t = t_1, t_1 + 1, .., T$. Hence, stand development can be described by the difference

129   equations

130   (1) $x_{1,t+1} = \phi(\mathbf{x}_t) + [1 - \beta_1(\mathbf{x}_t) - \mu_1(\mathbf{x}_t)] x_{1t} - h_{1t}$,

131   (2) $x_{s+1,t+1} = \beta_s(\mathbf{x}_t) x_{st} + [1 - \beta_{s+1}(\mathbf{x}_t) - \mu_{s+1}(\mathbf{x}_t)] x_{s+1,t} - h_{s+1,t}$, $s = 1, 2, ..., n-2$,

132   (3) $x_{n,t+1} = \beta_{n-1}(\mathbf{x}_t) x_{n-1,t} + [1 - \mu_n(\mathbf{x}_t)] x_{nt} - h_{nt}$,

133   where $t = t_1, t_1 + 1, ..., T$.

134   We assume that the stand is artificially regenerated after a clearcut, and the time interval

135   between the regeneration activities and the ingrowth of trees into the smallest size class equals a

136   certain number of periods denoted by t_1. Thus, t_1 periods after planting, we have an initial stand

137   composed of a given number of trees in size class 1. The stand is clearcut if the rotation length

138    $T \in [t_1, \infty)$ is finite.

139   Let $w \geq 0$ (€ ha^{-1}) denote the cost of artificial regeneration. We denote the discount factor by

140    $b = 1/(1+r)$, where r refers to the annual interest rate. The length (in years) of a period is denoted by

141   Δ. Revenues, $R(\mathbf{h}_t)$ from thinning and $R(\mathbf{x}_T)$ from clearcuts, depend on the number and size of

142   trees harvested. The revenues per period are specified as

143   (4) $R(\mathbf{h}_t) = \sum_{s=1}^{n} h_{st} (v_{\sigma,s} p_\sigma + v_{\varpi,s} p_\varpi), \ t = t_1, t_1 + 1, \dots T$,

144   where $v_{\sigma,s}$ and $v_{\varpi,s}$ are the sawlog and pulpwood volumes in a tree of size class s, and p_σ and p_ϖ

145   are the respective (roadside) prices (€ m^{-3}). Variable harvesting costs (for cutting and hauling) are

146   given separately for thinning and clearcuts by $C_i(\mathbf{h}_t)$, $i = th, cl$. A fixed harvesting cost denoted by

147   C_f covers e.g. the transportation of machinery to the stand site. Because of the fixed cost it may not

148   be optimal to harvest the stand in every period. This is taken into account by the binary variables

149    $\delta_t \in \{0,1\}$, $t = t_1, t_1 + 1, \dots, T$ and by the Boolean operator $h_t = \delta_t h_t$. When the choice is $\delta_t = 1$, the

150   levels of $h_{st} \geq 0$, $s = 1, 2, \dots, n$ can be freely optimized. When $\delta_t = 0$, the only admissible choice is

151    $h_{st} = 0$, $s = 1, 2, \dots, n$.

152   As carbon storage in forests is a positive externality, we assume a Pigouvian subsidy system

153   resembling the one in van Kooten et al. (1995). Accordingly, society pays the forest owner for the

154   amount of CO_2 that is absorbed as the stand grows, and charges for the amount of CO_2 that is released

155   as a consequence of harvesting and natural mortality. Let $p_c \geq 0$ (€ tCO$_2$$^{-1}$) denote the economic

156 value of CO_2. We let $\omega_t = \sum_{s=1}^{n} x_{s,t} \left(v_{\sigma,s} + v_{\varpi,s} \right)$ denote the merchantable timber volume (i.e. stem

157 volume) of the stand at the beginning of period t. Density factor ρ converts stem volume into stem

158 dry mass. In addition to the stem, trees are comprised of non-merchantable matter, i.e. foliage,

159 branches, bark, stumps and roots. Expansion factor η converts stem dry mass into whole tree dry

160 mass. Hence, the total tree biomass in the stand at the beginning of period t can be given as

161 $B_t \left(\mathbf{x}_t \right) = \rho \eta \omega_t$, and net biomass growth in period t as $B_{t+1} \left(\mathbf{x}_{t+1} \right) - B_t \left(\mathbf{x}_t \right)$. The amount of CO_2 in one

162 dry mass unit equals θ.

163   We denote the dry mass of sawlog and pulpwood harvested at the end of period t by

164 $y_{\sigma,t} = \rho \sum_{s=1}^{n} h_{st} v_{\sigma,s}$ and $y_{\varpi,t} = \rho \sum_{s=1}^{n} h_{st} v_{\varpi,s}$, respectively. Logging will not instantly release the

165 carbon content of timber into the atmosphere because it is only gradually released from timber

166 products as they decay (Liski et al. 2001). Dead tree matter is created both through natural mortality

167 and from harvest residues (i.e. non-merchantable parts of the harvested trees) left in the forest. The

168 dry mass of dead tree matter formed through natural mortality in period t equals

169 $d_{m,t} = \rho \eta \sum_{s=1}^{n} \mu \left(\mathbf{x}_t \right)_{s,t} x_{s,t} \left(v_{\sigma,s} + v_{\varpi,s} \right)$. Further, the dry mass of harvest residues created at the end of

170 period t can be given as $d_{h,t} = \left(\eta - 1 \right) \left(y_{\sigma,t} + y_{\varpi,t} \right)$. We denote the annual decay rates of sawlog,

171 pulpwood and dead tree matter, respectively, by g_j ($j = \sigma, \varpi, d$). The urgency of mitigating climate

172 change implies that society is likely to have a positive time preference for net emissions. It can be

173 shown that, per unit of wood product or dead tree matter, the present value of future emissions due to

174 decay equals $p_c \alpha_j \left(r \right)$, where

175 (5) $\alpha_j \left(r \right) = \dfrac{g_j}{g_j + r}$

176 (cf. Pihlainen et al. 2014, Assmuth and Tahvonen 2017).

177   Thus the economic value of net carbon sequestration (or net negative emissions) in period t can

178   be given as

179   (6) $Q_t = p_c \theta \left\{ B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t) + \left[1 - \alpha_\sigma(r) \right] y_{\sigma,t}(\mathbf{h}_t) + \left[1 - \alpha_\varpi(r) \right] y_{\varpi,t}(\mathbf{h}_t) + \left[1 - \alpha_d(r) \right] \left(d_{m,t}(\mathbf{x}_t) + d_{h,t}(\mathbf{h}_t) \right) \right\}$

180   for $t = t_1, t_1 + 1, ..., T$,

181   where $B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t)$ refers to net growth, i.e. the change in biomass net of harvests. The

182   additional elements $\left[1 - \alpha_\sigma(r) \right] y_{\sigma,t}(\mathbf{h}_t)$ and $\left[1 - \alpha_\varpi(r) \right] y_{\varpi,t}(\mathbf{h}_t)$ are needed to take into account

183   that harvested trees are used for sawlog and pulpwood products, respectively, which release their

184   carbon content as they decay. Correspondingly, $\left[1 - \alpha_d(r) \right] \left(d_{m,t}(\mathbf{x}_t) + d_{h,t}(\mathbf{h}_t) \right)$ refers to dead tree

185   matter (from natural mortality and harvest residue) and its decay.

186   The problem of optimizing harvests over an infinite horizon can now be given as

187   (7) $J(\mathbf{x}_0, T) = \max_{\{ h_{st}, \delta_t, T \in [t_1, \infty) \}} \dfrac{-w + \sum_{t=0}^{T} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t+1)} + \sum_{t=t_1}^{T} \left[R(\mathbf{h}_t) - C_i(\mathbf{h}_t) - \delta_t C_f \right] b^{\Delta(t+1)}}{1 - b^{\Delta(T+1)}}$

188   s.t. (1) – (3) and

189   (8) $\delta_t \in \{0,1\}$, $t = t_1, t_1 + 1, ..., T$

190   (9) $x_{st} \geq 0$, $s = 1, 2, ..., n$, $t = t_1, t_1 + 1, ..., T + 1$,

191   (10) $h_{st} = \delta_t h_{st} \geq 0$, $s = 1, 2, ..., n$, $t = t_1, t_1 + 1, ..., T$,

192   (11) $\mathbf{x}_{T+1} = 0$,

193   (12) x_{s,t_1} given.

194   The optimal forest management regime is determined by the choice of T. If – given optimized

195   thinnings – the objective functional is maximized by a finite rotation age, rotation forestry is optimal.

196   If no maximum exists and the bare land value converges toward the continuous cover forestry bare

197   land value from below as $T \to \infty$, then it is optimal to apply continuous cover management.

198   3. Ecological and economic parameter values

199   We apply an empirical growth model by Bollandsås et al. (2008) for Norway spruce at latitude 61.9

200   ºN. The model has been estimated using the National Forest Inventory of Norway, and includes

201   functions for ingrowth, mortality and diameter increment. We study an average productivity site (

202    $SI = 15$), implying that the height of the dominant trees at the age of 40 (100) years is 15 (24) metres.

203   We use 12 size classes with diameters (midpoints) ranging from 7.5 cm to 62.5 cm with 5.0 cm

204   intervals. Table 1 presents the size class -specific parameter values (Rämö and Tahvonen 2014). The

205   length of a period (Δ) is five years and the time interval from planting to the emergence of trees into

206   the first size class is 20 years (i.e. $t_1 = 4$). The initial stand structure is given as $\mathbf{x} = [2250, 0, 0, \ldots]$,

207   i.e. 20 years after artificial regeneration, 2250 trees emerge in the smallest size class.

208   The estimated natural mortality during the 5-year period t in size class s is given as

209    $\mu_{st} = \left(1 + e^{-\left(-2.492 - 0.020M_s + 3.2 \cdot 10^{-5}M_s{}^2 + 0.031A_t\right)}\right)^{-1}$, where M_s is the diameter (midpoint) of size class

210   s and A_t the total stand basal area (m^2 ha^{-1}) at the beginning of period t. The fraction of trees

211   moving to the next size class during period t is denoted by

212    $\beta_{st} = \left(1.2498 + 0.0476M_s - 11.585 \cdot 10^{-5}M_s{}^2 - 0.3412L_{st} + 0.906 \cdot SI - 0.024A_t\right)/50$,

213   where L_{st} is the total basal area of size classes $s + 1,...,n$ at the beginning of period t. The estimated

214   number of trees entering the smallest size class (i.e. natural regeneration) during the 5-year period t

215   is given as $\phi_t = \dfrac{54.563\left(A_t + a\right)^{-0.157} \cdot SI^{0.368}}{1 + e^{\left(0.391 + 0.018A_t - 0.066 \cdot SI\right)}}$.

216   Note that ϕ is strictly convex in $\mathbf{x}$, implying nonconvexities in the optimization problem. In

217   Bollandsås et al. (2008), $a = 0$ and $\phi \to \infty$ as $\mathbf{x} \to 0$. This feature is unwarranted, and based on

218   Wikberg (2004) and Pukkala et al. (2009) we set $a = 0.741$, which implies $\phi(0) = 100$. This

219   correction parameter decreases the ingrowth by less than one tree per year when basal area is above

220   2 m^2.

221   The roadside prices for sawtimber and pulpwood are €58.44 m^{-3} and €34.07 m^{-3}, respectively.

222   The fixed harvesting cost equals €500 ha^{-1}. For the variable harvesting costs we use empirically

223   estimated functions by Nurminen et al. (2006), based on the performance of modern harvesters. The

224   variable harvesting costs (cutting and hauling) depend on the number and volumes of trees cut, and

225   are given separately for thinning and clearcuts as

226   $$C_i = C_{i0} C_{i1} \sum_{s=1}^{n} h_{st} \left(C_{i2} + C_{i3} v_s - C_{i4} v_s^2 \right) + C_{i5} \left[C_{i6} \sum_{s=1}^{n} h_{st} v_s + C_{i7} \left(\sum_{s=1}^{n} h_{st} v_s \right)^{0.7} \right], \; i = th, cl.$$

227   C_{i0} is the per-minute cutting cost (€), and its coefficient $C_{i1}(\bullet)$ is the time (in minutes) spent cutting

228   one tree and moving the machinery to the next tree. C_{i5} and its coefficient $[\bullet]$ are the cost and time

229   spent in hauling, respectively, while $v_s = v_{\sigma,s} + v_{\varpi,s}$ is the volume of a tree in size class s. The

230   parameter values for C_{ik}, $i = th, cl$, $k = 0,...,7$ are given in Table 2. The parameter $C_{th1} = 1.150$ in the

231   cutting cost element for thinning takes into account that cutting one tree and moving to the next one

232   is more costly in (continuous cover) thinning compared to clearcuts (Surakka and Siren 2007).

233   Additionally, hauling is more time-consuming in thinnings than in clearcuts. The cost of artificial

234   regeneration is €1000–1500 ha^{-1} (Niinimäki et al. 2012). We apply the lower bound because this will

235   reveal how carbon storage alters the choice between continuous cover and rotation forestry.

236   Based on Lehtonen et al. (2004), the stemwood density factor (ρ) for Norway spruce is 0.3774

237   tonnes of dry matter per cubic metre of fresh volume, and the expansion factor to convert stem dry

238   mass into whole tree dry mass (η) equals 2.1566. Following Niinimäki et al. 2013, the CO_2 content

239   of a wood dry mass unit (θ) is obtained by multiplying the share of carbon in biomass dry weight

240   (0.5) with the coefficient that converts tonnes of carbon to tonnes of CO_2 (44/12). Thus we set

241   $\theta = 1.83333$ tCO$_2$ t^{-1}. For the decay rate of dead tree matter we use $g_d = 0.18196$ based on the average

242 rate of stem, foliage, branches, bark, stumps and roots in Hyvönen and Ågren (2001). To obtain the

243 decay rates for sawlog and pulpwood products we use data presented in Liski et al. (2001) on the

244 division of sawlog and pulpwood removals for production lines, on production losses, and on the

245 division into timber product types with different lifespans. The obtained parameter values are $g_\sigma =$

246 0.06611 and $g_\varpi = 0.47070$.

247 4. Computational methods

248 Because the harvest timing variables are integers, but harvest intensities are continuous, the task is to

249 solve a mixed-integer nonlinear programming problem. To do this, we apply bilevel optimization

250 (Colson et al. 2007).[1] The lower-level problem is computed using version 9.0 of the Knitro

251 optimization software, which applies advanced gradient-based interior point algorithms (Byrd et al.

252 2006). The maximized objective value of the lower-level problem forms the objective value given

253 any vector of harvest timing binaries. The harvest timing vector is optimized using a genetic algorithm

254 (Deb and Sinha 2010, Sinha et al. 2017). The optimal harvest schedules are solved for a series of

255 rotation lengths. If the objective function obtains a maximum with some $T \in [60,180)$ years, the

256 optimal rotation is finite. If the value of the objective function continues to increase as the rotation

257 period is lengthened, the optimal rotation is infinite. In this case, the optimal continuous cover

258 solution is obtained by lengthening the horizon to obtain a close approximation of the infinite horizon

259 solution. To handle potential non-convexities, we apply multiple randomly chosen initial points in

260 the optimization. For the genetic algorithm, we use a randomly generated initial population of 40

261 harvest timing vectors, and for each harvest intensity optimization we use four random initial points.

262 These values were found to be sufficient for finding the same local optimum as a higher number of

263 initial guesses. Using efficient parallel computation (Intel (R) Xeon (R)E5-2643 v3 @3.40GHZ, 24

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[1] A similar approach has been applied to a forest management problem without carbon storage in Tahvonen and Rämö (2016).

264 logical processors), the optimal harvest intensity and timing is found within 3–36 h. The solution

265 times for the lower lever problem are typically 5–15 seconds with approximately 20% variability in

266 the objective values of the local optima based on different initial points.

267

268 5. Results

269 *The effects of carbon pricing on optimal stand management*

270 For reference, we first briefly state results for the generic Faustmann setting (Samuelson 1976), where

271 harvesting can be carried out solely in clearcuts (i.e. no thinnings), and no natural regeneration takes

272 place. This setting is similar to that of the carbon storage study by van Kooten et al. (1995). Given an

273 annual interest rate of 2%, with zero carbon price, the optimal rotation age is 60 years. Setting a

274 carbon price of €20 (€30) tCO_2^{-1} lengthens the optimal rotation period to 65 (70) years, while a carbon

275 price of €60 tCO_2^{-1} implies a 90-year rotation period. Given a 4% annual interest rate, the effect of

276 carbon pricing on rotation length is somewhat stronger. Increasing the carbon price from zero to €60

277 tCO_2^{-1} increases the optimal rotation age from 50 years to 110 years.

278   We now turn to the full economic setup with optimized intensity and timing of thinnings along

279 with an optimized rotation period and management regime. Given a 2% annual interest rate, optimal

280 rotation age increases with carbon price (Table 3, Figure 1). The optimal rotation length without

281 carbon pricing equals 130 years. The relatively long rotation follows from optimally utilizing natural

282 regeneration. When carbon price equals €10 (€20) tCO_2^{-1}, the rotation age is 150 (170) years. Given

283 a carbon price of €30 tCO_2^{-1} or higher, the optimal rotation period is infinitely long, implying that

284 continuous cover forestry is superior to rotation forestry. Given a 4% interest rate, the optimal rotation

285 is infinite even with zero carbon price (Table 3, Figure 2). This is because a high interest rate makes

286 it optimal to postpone or avoid the investment in artificial regeneration, as natural regeneration

287 maintains a sufficient level of growth without costs. Moreover, a higher interest implies lower optimal

13

288 stocking and thus a smaller opportunity cost of delaying the clearcut. Additionally, the time delay

289 between stand regeneration and the first revenues from thinnings becomes costly when discounting

290 is heavier. This encourages a shift to continuous cover forestry with more frequently repeated

291 harvests.

292   Regardless of management regime (rotation forestry or continuous cover forestry), optimal

293 thinning is invariably performed from above, always fully cutting down the largest harvested size

294 class. Relative value growth is very high in small trees, implying that it is optimal to postpone

295 harvesting until they have grown to a size that yields sawlog. Given a 2% interest rate and zero carbon

296 price, the first thinning takes place 45 years after stand regeneration (Table 3, Figure 1). Carbon

297 pricing postpones the first thinning by five years, and increases mean stand volume along the rotation

298 – or, in the case of continuous cover solutions, at the steady state (Table 3). The timing and intensity

299 of subsequent thinnings can be seen in Figure 1, where stand volume and the number of trees drop

300 after each harvest. Given a 4% interest rate and no carbon pricing, the first thinning is carried out

301 already at a stand age of 40 years (Table 3, Figure 2), as it is optimal to maintain less capital in the

302 stand. A carbon price of €20 (€60) tCO_2^{-1} postpones the first thinning by five (15) years.

303   The relative effect of carbon pricing on optimal stand management and stand density is larger

304 with a higher interest rate. Given a 2% interest rate, mean stand volumes range from 138 to 224 m^3

305 ha^{-1} for carbon prices €0–€60 tCO_2^{-1}; given a 4% interest rate the corresponding mean stand volumes

306 span from 68 to 234 m^3 ha^{-1} (Table 3). From the economic point of view, forest carbon storage

307 essentially means shifting net emissions forward in time. Thus stronger discounting implies a stronger

308 incentive to adapt forest management to provide more carbon storage.

309   The higher the carbon price, the larger the harvested trees at the continuous cover steady states

310 (Table 3, Figure 3). Additionally, the number of size classes harvested equals the number of five-year

311 periods between the steady-state harvests. Given a 2% interest rate and a carbon price of €30 tCO_2^{-1},

312 trees are harvested from five size classes in the optimal continuous cover solution (diameter midpoints

313   32.5, 37.5, 42.5, 47.5 and 52.5 cm) with a 25-year interval. When carbon price increases to €60 tCO_2^-

314   ^{1}, it is optimal to forgo harvesting the 32.5 cm diameter class and to only cut trees with diameters of

315   37.5–52.5 cm. This is achieved by switching to a 20-year harvesting interval (Table 3). Thus harvest

316   timing adjusts to the carbon price to maintain optimal average stand density and economic return

317   (including carbon subsidies) along the harvest interval.

318   Given a 4% interest rate and zero carbon price, the steady-state harvest takes place every 20

319   years, and targets trees with diameters of 22.5–37.5 cm (Table 3, Figure 3). With a €10 tCO_2^{-1} carbon

320   price, the steady-state harvesting interval equals 25 years, allowing some trees to enter the 42.5 cm

321   size class before they are harvested. Increasing the carbon price further shifts the steady-state harvests

322   to larger size classes, implying a higher mean stand volume. While the number of trees decreases

323   with tree size class (Figure 3, column a), large trees comprise a considerable fraction of the total stem

324   volume because of their high volume per tree (Figure 3, column b).

325

326   *The effects of carbon pricing on timber production and carbon storage*

327   Given a 2% interest rate and zero carbon price, mean annual sawlog yield over the rotation equals 6.3

328   m^3 ha^{-1}, while mean annual total yield (sum of sawlog and pulpwood) equals 7.6 m^3 ha^{-1} (Table 4).

329   Increasing the carbon price to €10 (€20) tCO_2^{-1} increases mean sawlog yield to 6.5 (6.7) m^3 ha^{-1} while

330   total yield remains unchanged, i.e. the sawlog-pulp ratio increases. This has a positive effect on

331   carbon storage because the typical decay rate of sawlog products is notably slower than that of

332   pulpwood. Increasing the carbon price to €30 tCO_2^{-1} implies a regime shift from rotation forestry to

333   continuous cover forestry, and decreases mean sawlog and total yield while increasing the sawlog

334   ratio. The explanation is that continuous cover management tends to produce somewhat lower mean

335   yields than rotation forestry, even when the bare land value of the former is higher. Increasing the

336   carbon price further, to €60 tCO_2^{-1}, has only a negligible effect on mean sawlog and total yields.

337   Given a 4% interest rate and no carbon pricing, mean sawlog and total yields are low, 3.8 and

338   4.5 m^3 ha^{-1} a^{-1}, respectively (Table 4). This is due to the low optimal level of growing capital. With

339   carbon pricing, trees are allowed to grow bigger before they are harvested (Table 3), which increases

340   yields when the carbon price is relatively low. For example, given a carbon price of €30 tCO_2^{-1}, the

341   mean sawlog yield equals 5.7 m^3 ha^{-1} and mean total yield is 6.7 m^3 ha^{-1}. However, with €60 tCO_2^{-1}

342   carbon price, mean sawlog and total yields equal 5.6 and 5.8 m^3 ha^{-1}, respectively (Table 4). This

343   implies that when the carbon price is sufficiently high, yields begin to decrease with carbon price

344   because only very large trees are harvested.

345   Natural mortality remains rather low in economically optimal solutions, but dead tree matter is

346   generated from harvest residues. Each harvest decreases the carbon storage in living trees, but causes

347   a temporary increase in carbon storage in dead tree matter and in timber products (Figure 4). The

348   latter two, however, quickly decrease as a consequence of decay. This is especially true for clearcuts

349   (Figure 4a–c), which yield large amounts of rapidly decaying pulpwood. Because of exponential

350   decay, the initial carbon stocks in dead tree matter and in timber products reach a steady state, where

351   total carbon storage at the beginning of the rotation equals total carbon storage at the end of the

352   rotation. In continuous cover solutions (Figure 4d), carbon stocks in living trees, dead tree matter and

353   timber products go through a transition phase before reaching a steady state.

354   Mean carbon storage in living trees increases with carbon price (Table 4). For example, given

355   a 2% interest rate and no carbon pricing, the average amount of carbon stored in living trees over a

356   rotation is 207 tCO_2 ha^{-1}; increasing the carbon price to €60 tCO_2^{-1} increases mean storage to 335

357   tCO_2 ha^{-1}. Additionally, mean carbon storage in dead tree matter and timber products generally

358   increase with carbon price. An exception is the regime shift from rotation forestry to continuous cover

359   forestry (2% interest rate, carbon price from €20 to €30 tCO_2^{-1}). As mentioned, rotation forestry

360   produces high total yields and thus large amounts of harvest residues, and average natural mortality

361   is somewhat higher in rotation forestry than in continuous cover forestry. Moreover, the calculation

362   of mean carbon storage in dead tree matter and timber products takes into account the accumulation

363   of these stocks from one rotation to the next.

364   In solutions where continuous cover management is optimal, the steady state may be reached

365   as late as approximately 300 years after stand regeneration. This implies that in terms of economic

366   outcome, the carbon storage taking place during the long transition phase towards the steady state is

367   likely to be more important than mean carbon storage. Discounted CO_2 sequestration (tCO_2 ha^{-1}) is

368   the sum of all periodic net carbon fluxes within the infinite planning horizon, each discounted to the

369   present (stand regeneration) moment. For example, given a 2% interest rate and a carbon price of €20

370   tCO_2^{-1}, the net carbon sequestration over the infinite horizon is equivalent to 232 tonnes of CO_2

371   emissions abated immediately. Discounted CO_2 sequestration increases monotonously with carbon

372   price (Table 4).

373   *Forestry revenues and the cost of carbon storage*

374   The higher the carbon price, the lower the discounted timber income (Table 5). This is true despite of

375   the fact that the mean timber yields do not monotonically decrease with carbon price (Table 4). The

376   decrease in discounted timber income is partly explained by differences in harvest timing: when

377   carbon storage is valued, harvests are carried out later. Additionally, deviating from the optimal

378   timber-only solution implies higher harvesting costs per timber unit. However, the decrease in timber

379   income is more than compensated by carbon subsidies that represent the economic value of carbon

380   storage. Including carbon storage benefits improves net present values (i.e. bare land value)

381   considerably: given a 2% (4%) interest rate, a carbon price of €20 tCO_2^{-1} increases net present value

382   by 50% (137%) (Table 5). If the social value of carbon storage is high (€30 or €60 tCO_2^{-1} depending

383   on interest rate), the economic benefits from carbon storage clearly overweigh the income from timber

384   production.

385   The economic cost of additional carbon storage, i.e. the cost of carbon abatement in forestry, is

386   measured as lost timber income. To obtain marginal abatement costs, we divide the incremental

387 decrease (i.e. from the solution with a lower carbon price) in timber income for each optimal solution

388 by the corresponding incremental increase in discounted CO_2 sequestration.[2] Marginal abatement

389 costs increase with the amount of carbon abatement (Figure 5). Given a 2% interest rate, marginal

390 costs range from €3 to €46 tCO_2^{-1} for 10 to 70 tonnes of carbon abatement per hectare. Given a 4%

391 interest rate abatement is somewhat more costly, but carbon abatement up to 33 tonnes per hectare

392 can be achieved with a marginal cost below €40 tCO_2^{-1}.

393 6. Discussion and conclusions

394 It is widely established in the literature that valuing carbon storage increases optimal rotation age in

395 even-aged forestry (e.g. van Kooten et al. 1995, Stainback and Alavalapati 2002, Gutrich and

396 Howarth 2007, Pohjola and Valsta 2007). While our findings support this result, our model differs

397 from previously published models in many important aspects and is able to shed light on previously

398 unaddressed questions. Unlike many studies, we include thinnings, and optimize their timing along

399 with their intensity. Further, we determine the optimal management regime – rotation forestry or

400 continuous cover forestry – endogenously. As far as we know, such an optimization approach has not

401 been combined with carbon storage using a size-structured description of forest resources.

402 　　　　Including thinnings (and natural regeneration) is essential for our approach, because it implies

403 that timber revenues may be obtained from a forest that is never clearcut. This is not the case in

404 studies applying the classic Faustmann rotation model, e.g. van Kooten et al. (1995) and Hoel et al.

405 (2014). van Kooten et al. (1995) find that carbon pricing generally increases rotation ages only

406 moderately, but in certain cases might yield a result where it is optimal to forgo harvesting completely.

407 Hoel et al. (2014) show that rotation age typically increases with the social cost of carbon and may

408 become infinitely long (i.e. forestry is abandoned). According to our results, carbon pricing may

409 indeed render the optimal rotation infinitely long, but instead of total abandonment of harvesting as

---

[2] Note that an amount of discounted CO_2 sequestration corresponds to an equal amount of emissions abated immediately.

410 in van Kooten et al. (1995) and Hoel et al. (2014), it then becomes optimal to manage the stand with

411 thinnings (i.e. apply continuous cover forestry).

412   According to studies that included optimized thinnings in their even-aged setup (e.g. Pohjola

413 and Valsta 2007, Daigneault et al. 2010, Niinimäki et al. 2013), carbon pricing tends to postpone

414 thinnings, increase mean stand volume and lengthen the optimal rotation period. Our results support

415 these findings. However, our generalized model yields optimal solutions that go beyond the scope of

416 earlier studies limited to forests without natural regeneration. Given the low interest rate (2%),

417 optimal rotations are long, ranging from 130 to 170 years for carbon prices €0–€20 tCO_2^{-1}. With a

418 €30 tCO_2^{-1} carbon price, clearcutting is suboptimal, i.e. the optimal management regime switches

419 from rotation forestry to continuous cover forestry. Given a higher interest rate (4%), continuous

420 cover forestry dominates rotation forestry regardless of carbon price[3], and management adapts to

421 carbon pricing by changing the timing and targeting of thinnings.

422   In our model setup, it is possible to exclude natural regeneration by setting $\phi(\mathbf{x}_t) = 0$ in Eq. 1

423 (implying that any naturally regenerated saplings are cleared away, and the clearing is costless). If

424 this is done, we obtain optimal rotation ages that are well in line with those obtained in earlier studies

425 on even-aged Norway spruce: the study by Solberg and Haight (1991) based on a size-structured

426 growth model, and the study by Niinimäki et al. (2013) utilizing a highly detailed process-based

427 model. Without natural regeneration and given a 2% interest rate, our optimal rotation lengths range

428 from 100 to 155 years for carbon prices €0–€60 tCO_2^{-1}. Given a 4% interest rate, rotation periods for

429 carbon prices €0–€30 tCO_2^{-1} span from 100 to 130 years, while a carbon price of €60 tCO_2^{-1} yields an

430 optimal rotation as long as 215 years.

431   With the exception of Goetz et al. (2010), studies on uneven-aged management with carbon

432 storage tend to apply static optimization, which does not allow optimizing stand transition from any

---

[3] This is in line with Tahvonen and Rämö (2016), where high site productivity, low interest rate and low regeneration cost favour the clearcut regime instead of continuous cover regime, and *vice versa*.

433   initial state that is not close to the steady state (e.g. Pukkala et al. 2011, Buongiorno et al. 2012).

434   Further, as far as we know, our study presents the first results on optimal harvest timing in uneven-

435   aged forestry with carbon storage. Our results suggest that when beginning with bare land, the large

436   initial cohorts are intensively utilized in a series of thinnings before approaching the steady state, and

437   that these thinnings are postponed and moderated by carbon pricing. Reaching the steady state may

438   take as much as 300 years from stand regeneration, which emphasizes the importance of the transition

439   phase for the present value of net revenues from both timber production and carbon storage. We also

440   show that the steady-state harvesting interval, along with the diameter distribution of the standing and

441   harvested trees, react to changes in carbon price. The average size of the harvested trees increases

442   with carbon price, and four (or five) diameter classes are fully harvested each 20 (25) years at the

443   steady state.

444   The carbon storage formulation presented in van Kooten et al. (1995) takes into account that

445   while carbon is stored in living trees, it may also be stored to some extent in timber products. We add

446   detail to this formulation by explicitly including carbon storage in timber products and in dead tree

447   matter. Our results suggest that a small carbon stock is maintained in dead tree matter, formed from

448   harvest residues and through natural mortality. To account for carbon storage in timber products, we

449   use distinct decay rates for sawlog and pulpwood (cf. Pihlainen et al. 2014). This is important because

450   our size-structured model enables us to direct thinnings to trees of specific size, making use of the

451   fact that large trees yield relatively more sawlog than small trees. Sawlog, in turn, is superior to

452   pulpwood in its ability to store carbon for extended periods. Such targeted harvesting is by definition

453   impossible in clearcuts, which inevitably results in the harvesting of quickly decaying pulpwood. This

454   becomes costly with a high carbon price. Hence the impact of carbon storage on the relative

455   profitability of rotation forestry *vs*. continuous cover forestry cannot be fully captured by a model that

456   omits the size structure of the stand, or the varying decay profiles of timber assortments. According

457 to our results, carbon pricing indeed increases the sawlog-pulp ratio of the mean annual yield and

458 may induce a regime shift to continuous cover forestry.

459   The model developed in this study is a stand-level model, and thus does not include market

460 interactions. However, our results yield some initial understanding on the effects of carbon storage

461 on wood supply. In general, carbon pricing increases mean total annual yields, mostly due to

462 increased sawlog production. The only exception to this is the case with a low interest rate (2%),

463 where a carbon price of €30 tCO_2^{-1} induces a shift from rotation forestry to continuous cover

464 management with somewhat lower mean yields. Given an interest rate equal or above 4%, continuous

465 cover management with fairly low stand density is optimal when carbon storage is not valued, and

466 carbon pricing clearly increases stocking levels along with the yields.

467   The cost of artificial regeneration has a large effect on the relative profitability of continuous

468 cover and rotation forestry (Tahvonen and Rämö 2016). In this study, we have assumed the cost of

469 artificial regeneration to be €1000 ha^{-1}, which is on the lower side of the typical cost range in Finland.

470 If the regeneration cost is set higher, e.g. €2000, continuous cover management is optimal regardless

471 of carbon price even with low interest rates. Low site productivity has a similar effect.

472   McKinsey & Company (2009) estimates a global abatement potential of almost 8000 $MtCO_2$

473 per year in the forestry sector for a marginal cost range from €2 to €28 tCO_2^{-1}. In van Kooten et al.

474 (2009), a meta-regression analysis of forest carbon storage costs is performed using 1047

475 observations from 68 studies. Depending on the regression model used, the authors obtain highly

476 varying estimates on the marginal costs of carbon storage. According to van Kooten et al. (2009),

477 storage costs are higher in the boreal region than in the tropics or than the global average. Within the

478 boreal region, their estimates are roughly equal to €4–€94 tCO_2^{-1} for plantation activities and 34–

479 €155 tCO_2^{-1} for adaptation of forest management. However, Niinimäki et al. (2013) show that

480 optimizing the stand management of Norway spruce yields additional discounted carbon storage up

481   to 40 tCO_2 ha^{-1} with marginal costs in the range of €6–€36 tCO_2^{-1}.[4] Our results, obtained using a stand-

482   level model with optimized management regime choice, point to a cost range of €5–€47 tCO_2^{-1} with

483   as much as 70 tCO_2 ha^{-1} of abatement potential. This suggests that if all relevant aspects of forest

484   management adaptation are optimized, increasing carbon storage can be relatively inexpensive even

485   in the boreal region.

486   In 2015 the European Union (EU) committed to reducing its domestic greenhouse gas emissions

487   by at least 40% from the 1990 level by 2030 (European Commission 2015). According to an impact

488   assessment by the Commission, fulfilling this commitment would imply a carbon price in the range

489   of €11–€53 tCO_2^{-1} (depending on policy scenario) in the EU Emissions Trading Scheme (ETS) by

490   2030. The range of projected prices in 2050 is €85–€264 tCO_2^{-1} (European Commission 2014, p. 80–

491   81.) Such carbon price levels would incentivize major changes in forest management, if carbon

492   storage in forests was linked to the ETS. Currently, however, New Zealand is the only country that

493   has integrated forest carbon storage in its emissions trading system (Adams and Turner 2012).

494   Whether or not similar approaches will be adopted in the EU and elsewhere, forest carbon storage is

495   likely to play an important role in any cost-effective climate change abatement strategy.

496   We have presented a way to study economically optimal carbon storage in forestry without

497   limiting the analysis to either even-aged or uneven-aged forestry. By determining the optimal

498   management regime endogenously, we can cover both regimes simultaneously and analyse the effect

499   of carbon storage on the optimal choice between them. We show that higher stand density, long

500   rotations and a possible switch to continuous cover management, with an emphasis on harvesting

501   large trees with a high sawlog ratio, are the economically efficient carbon abatement methods in stand

502   management. Optimal regime shifts between rotation forestry and continuous cover forestry in size-

503   structured stands have not previously been addressed in the carbon storage literature. The importance

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[4] Goetz et al. (2010) present even lower cost ranges for uneven-aged forestry in Spain, especially if soil carbon is taken into account.

504 of our results is further emphasized by recent arguments that forest heterogeneity (age, size and

505 species structure) may improve forest resilience under disturbances caused by climate change

506 (Gamfeldt et al. 2015). The next step, then, will be to optimize carbon storage and wood production

507 in mixed-species stands.

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Tables

Table 1. Size class -specific parameter values, per tree.

Size class	Diameter (cm)	Basal area (m^2)	Sawlog volume, $SI = 15$ (m^3)	Pulpwood volume, $SI = 15$ (m^3)
1	7.5	0.004	0.000	0.014
2	12.5	0.012	0.000	0.067
3	17.5	0.024	0.000	0.167
4	22.5	0.040	0.234	0.081
5	27.5	0.059	0.446	0.065
6	32.5	0.083	0.684	0.060
7	37.5	0.110	0.963	0.050
8	42.5	0.142	1.253	0.050
9	47.5	0.177	1.574	0.043
10	52.5	0.216	1.900	0.039
11	57.5	0.260	2.214	0.033
12	62.5	0.307	2.565	0.031

Table 2. Parameter values for the harvesting cost function.

i	C_{i0}	C_{i1}	C_{i2}	C_{i3}	C_{i4}	C_{i5}	C_{i6}	C_{i7}
th	2.100	1.150	0.412	0.758	0.180	1.000	2.272	0.535
cl	2.100	1.000	0.397	0.758	0.180	1.000	1.376	0.393

Table 3. Effect of carbon pricing on optimal stand management, given €1000 ha^{-1} regeneration cost.

Interest rate	Carbon price	Rotation age	Timing of first harvest	Harvest interval at steady state	Diameters of trees harvested at steady state	Mean stand volume
	(€ tCO$_2$$^{-1}$)	(years)	(years from stand regeneration)	(years)	(cm)	(m^3 ha^{-1})
2%	0	130	45	–	–	138
	10	150	45	–	–	152
	20	170	50	–	–	174
	30	∞	50	25	32.5–52.5	182
	60	∞	50	20	37.5–52.5	224
4%	0	∞	40	20	22.5–37.5	68
	10	∞	45	25	22.5–42.5	79
	20	∞	45	20	27.5–42.5	114
	30	∞	50	20	32.5–47.5	169
	60	∞	55	25	37.5–57.5	234

Table 4. Effect of carbon pricing on timber production and carbon storage, given €1000 ha^{-1} regeneration cost.

Interest rate	Carbon price	Rotation age	Mean annual sawlog / total yield	Mean CO$_2$ storage in living trees	Mean CO$_2$ storage in dead tree matter	Mean CO$_2$ storage in timber products	Discounted CO$_2$ sequestration
	(€ tCO$_2$$^{-1}$)		(m^3 ha^{-1} a^{-1})	(tCO$_2$ ha^{-1})	(tCO$_2$ ha^{-1})	(tCO$_2$ ha^{-1})	(tCO$_2$ ha^{-1})
2%	0	130	6.3 / 7.6	207	53	80	198
	10	150	6.5 / 7.6	227	53	81	213
	20	170	6.7 / 7.6	260	54	83	232
	30	∞	5.7 / 6.0	271	43	69	244
	60	∞	5.7 / 6.0	335	44	70	269
4%	0	∞	3.8 / 4.5	101	30	48	108
	10	∞	4.0 / 4.7	118	32	51	115
	20	∞	5.0 / 5.6	170	38	62	123
	30	∞	5.7 / 6.1	252	43	70	133
	60	∞	5.6 / 5.8	349	43	67	144

Table 5. Forestry revenues, given €1000 ha^{-1} regeneration cost.

Interest rate	Carbon price	Discounted timber income	Discounted carbon subsidies	Net present value
	(€ tCO$_2$$^{-1}$)	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})
2%	0	9 863	0	8 780
	10	9 791	2 128	10 865
	20	9 514	4 648	13 127
	30	9 174	7 314	15 488
	60	8 000	16 127	23 127
4%	0	2 662	0	1 662
	10	2 610	1 148	2 758
	20	2 483	2 462	3 945
	30	2 233	3 992	5 225
	60	1 726	8 666	9 392

Figure captions

Figure 1. Stand volume and number of trees, with a 2% interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Note: $w = €1000\ ha^{-1}$.

Figure 2. Stand volume and number of trees, with a 4% interest rate and carbon prices €0 and €20 tCO_2^{-1}. Note: $w = €1000\ ha^{-1}$.

Figure 3. Optimal steady-state structures expressed as (a) number of trees and (b) commercial volume in each size class, with a 4% interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Size classes begin from a diameter of 7.5 cm and increase in 5-cm intervals. Note: $w = €1000\ ha^{-1}$.

Figure 4. Total carbon storage, including carbon storage in living trees, dead tree matter and timber products, with a 2% interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Note: $w = €1000\ ha^{-1}$.

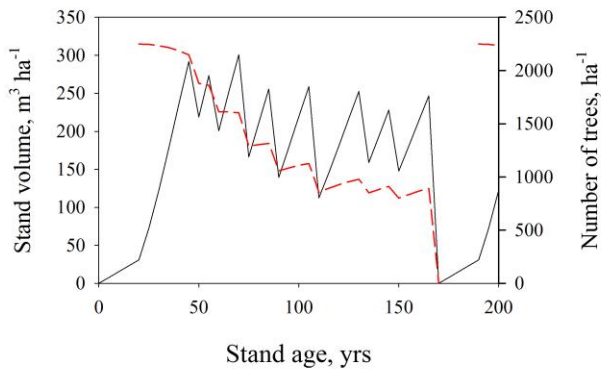Figure 5. Marginal abatement costs. Note: $w = €1000\ ha^{-1}$.
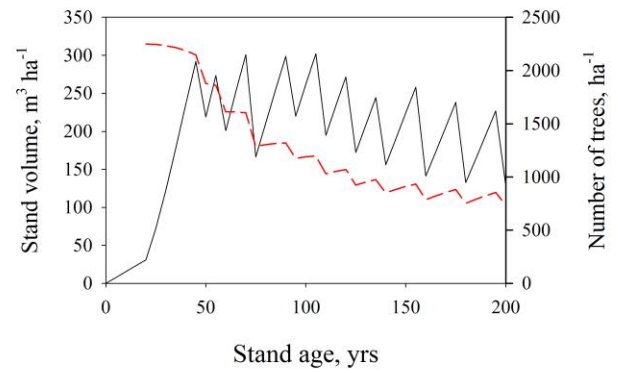
(a) $p_c = €0$ tCO$_2^{-1}$ (b) $p_c = €10$ tCO$_2^{-1}$
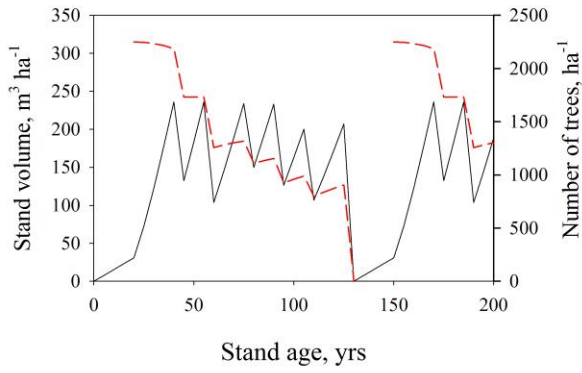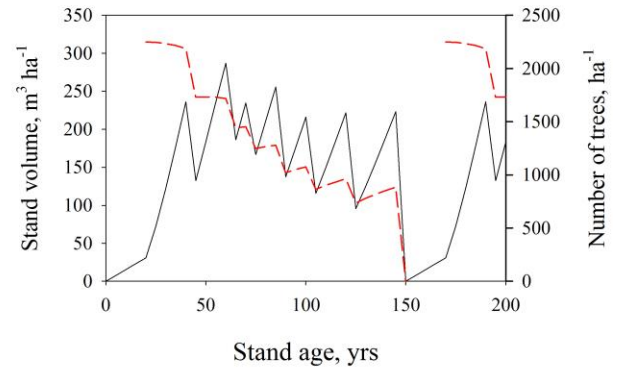
(c) $p_c = €20$ tCO$_2^{-1}$ (d) $p_c = €30$ tCO$_2^{-1}$
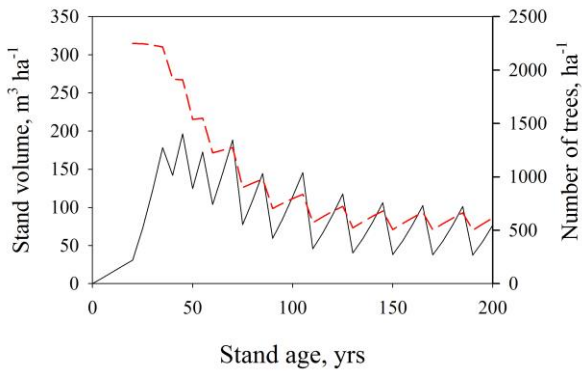
Stand volume, m^3 ha^{-1} Number of trees, ha^{-1}

(a) $p_c = €0$ tCO$_2^{-1}$ (b) $p_c = €20$ tCO$_2^{-1}$

Stand volume, m^3 ha^{-1} Number of trees, ha^{-1}

(a) $p_c = €0\ tCO_2^{-1}$

(b) $p_c = €10\ tCO_2^{-1}$

(c) $p_c = €20\ tCO_2^{-1}$

(d) $p_c = €30\ tCO_2^{-1}$

In living trees   In dead tree matter   In timber products

Marginal cost, € tCO$_2^{-1}$ (y-axis) vs Carbon abatement, tCO$_2$ ha^{-1} (x-axis)

- - - 2% interest rate
- · - 4% interest rate